Graded Bandgap Amorphous Silicon Germanium Alloy Solar Cells with Hydrogen Dilution Profiling

J. Yang, K. Lord, A. Banerjee, B. Yan, and S. Guha
United Solar Systems Corp.
1100 West Maple Road, Troy, Michigan 48084

ABSTRACT

Amorphous silicon (a-Si) and silicon germanium (a-SiGe) alloy *n i p* solar cells are investigated using various hydrogen dilutions during film growth to obtain intrinsic layers near the amorphous-to-microcrystalline transition. The on-the-edge 'transition' solar cells exhibit a reduction in the open-circuit voltage (V_{oc}) and a large dispersion of the V_{oc} values. Cells made beyond the threshold show low values of V_{oc}. The best solar cells are obtained using deposition conditions near but not on the edge. The transition for a-SiGe alloy solar cells occurs at a higher dilution than the a-Si alloy cells. An improved a-SiGe alloy solar cell is obtained by using a hydrogen dilution profile concurrent to the normal bandgap profiling.

1. Introduction

a-Si alloy solar cells and modules are receiving a great deal of attention as a low cost source of electrical generation. Achieving high efficiency is a key requirement to bring down the cost. We have reported a stable cell efficiency of 13% [1] using a triple-junction structure in which the bottom and the middle cells use a-SiGe alloys. Hydrogen dilution of the process gases has been extensively used to obtain high quality materials and solar cells. Hydrogen dilution is also known to promote growth of microcrystallites. The best quality material is grown at a dilution just below the threshold of amorphous-to-microcrystalline transition [2,3]. We have also shown [4] that the V_{oc} of solar cells decrease as the transition takes place; measurement of V_{oc} can, therefore, be used as a tool to determine at what thickness the material becomes microcrystalline. We have used this technique to investigate the transition in a-Si and a-SiGe alloys and find that the critical dilution depends on the Ge-content in the alloy. The highest quality [1] a-SiGe alloy cells use a profiling of Ge-content as a function of thickness to obtain a graded bandgap cell so as to aid minority carrier transport. We have, therefore, changed the amount of hydrogen dilution as the germanium concentration changes to obtain the optimum material throughout the thickness of the cell. This resulted in higher cell efficiency.

2. Experimental and Discussion

Single-junction *n i p* solar cells were grown on stainless steel (ss) substrates in a multichamber system. Small-area (≤0.25 cm^2) cells are obtained by depositing top contacts over the 4 cm x 4 cm substrate area. Gas mixtures of disilane in hydrogen and disilane and germane in hydrogen, respectively, were used to deposit the intrinsic layers of the a-Si and a-SiGe alloy solar cells. The hydrogen dilution was varied to obtain the threshold for amorphous-to-microcrystalline transition. The range of cell thickness investigated was between 1000 and 5000 Å, typically used in making high-efficiency solar cells.

Figure 1 shows the thickness dependence of the V_{oc} of a-Si alloy solar cells as a function of hydrogen dilution. R refers to the standard dilution that we use in our laboratory for obtaining the highest cell efficiency. For each experiment, several

devices are measured and data recorded. For low dilutions (0.5R to R), the V_{oc} is essentially independent of the intrinsic layer thickness for up to 5000 Å, indicating that the intrinsic layer is still amorphous. In these samples, the variation of V_{oc} on a given substrate is very small. As the dilution is increased to 1.2R and for a thickness of less than 3000 Å, the V_{oc} remains nearly constant. Beyond 3000 Å, however, some cells exhibit lower V_{oc}. For a thickness of 5000 Å, the dispersion in V_{oc} becomes large, and the lowest value of V_{oc} is lower than that of the 3000 Å cell. For the 1.4R samples, the value of V_{oc} becomes progressively lower and shows a spread even for a 1600 Å-thick device. In fact, the dispersion for the 5400 Å sample is as large as 200 mV. A higher dilution of 1.6R resulted in a further decrease in V_{oc}. In addition, as the cell thickness reaches 5000 Å, there is a substantial microcrystalline inclusion in the device, which is reflected by the smaller spread in V_{oc} and its low value. At the highest dilution (2R), V_{oc} drops to ~0.5 V even for the smallest thickness. A factor-of-two change in hydrogen dilution can result in a substantial change in V_{oc}, from 1 V to 0.5 V. When the material is 'on the edge', any small variation in deposition conditions can push the material over the edge. For the best quality material, it is thus advisable to find the "edge" conditions and then reduce the hydrogen dilution somewhat to arrive at a more desirable region.

The thickness dependence of V_{oc} on a-SiGe alloy solar cells with ~40% Ge has also been studied and the results are plotted in Fig. 2. The following observations are made. First, due to the narrow bandgap of the a-SiGe alloy, V_{oc} takes on lower values. Second, for a dilution of 1.4R, V_{oc} remains rather constant and without much dispersion for a thickness of up to ~3000 Å. This is in contrast to the case of a-Si alloy where 1.4R has already resulted in a spread in V_{oc} (see Fig. 1). Third, the amorphous-to-microcrystalline transition occurs at >1500 Å for the 1.9R cell, which is characterized by a lowering and
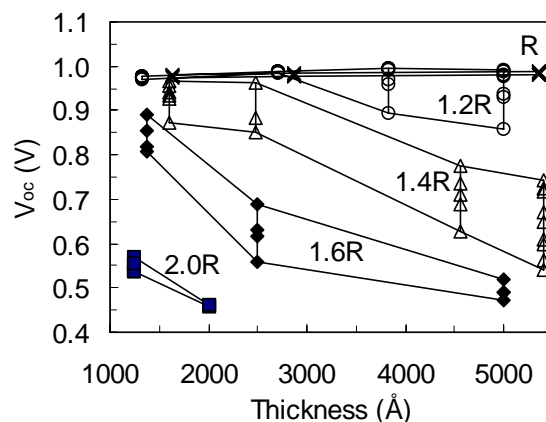

Fig 1. Thickness dependence of V_{oc} of a-Si alloy cells deposited with different hydrogen dilutions.
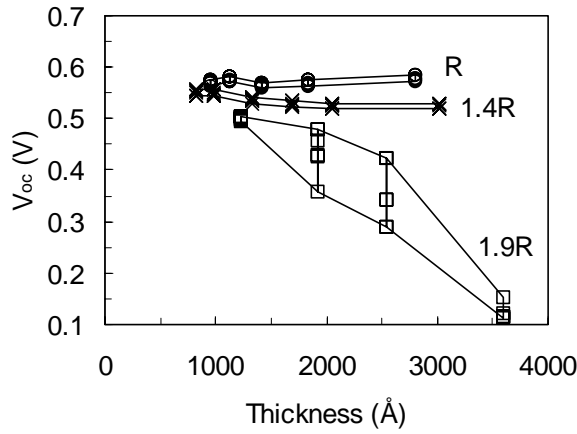
Fig 2. Thickness dependence of V_{oc} of a-SiGe alloy cells deposited with different hydrogen dilutions.

spread in V_{oc}. This is again in contrast with the a-Si alloy in that a dilution of 2R has already pushed a-Si alloys over the edge. We should also point out that the optimization of a-SiGe alloy solar cells is more complex than the a-Si alloy cells. Other deposition parameters can significantly influence the cell performance. While the dependence of V_{oc} on the thickness and dilution can serve as a guide to establish the threshold for a given set of deposition parameters, one must also optimize other conditions to assure good cell performance.

From Figs. 1 and 2 it is observed that for a cell thickness of ~2000 Å, the spread in Voc occurs near 1.4R for a-Si alloys, and near 1.9R for a-SiGe alloys. The fact that the critical dilution for amorphous-to-microcrystalline transition increases with incorporation of Ge is not surprising. It is well known [5] that one can obtain more ordered material if the adatom mobility of the impinging species on the growing surface is large. Hydrogen dilution is believed to passivate the growing surface so as to increase the adatom mobility, and this explains the improved order with increasing hydrogen dilution resulting eventually in the formation of microcrystallites. The predominant species for the growth of high quality a-SiGe alloys are SiH_3 and GeH_3. Since GeH_3 is heavier than SiH_3, a higher hydrogen dilution is necessary as the Ge-content increases to give the GeH_3 species enough mobility at the growing surface.

We have previously shown [6] that profiling of Ge-concentration as a function of thickness increases the built-in field within the cell and helps the hole transport. The highest cell efficiency was obtained when the Ge-concentration was changed continuously with the amount being maximum near the p-i interface. Since the optimum hydrogen dilution depends on the Ge-concentration, we have changed the hydrogen dilution during the growth of the intrinsic layer as a function of thickness with the dilution being the largest when the Ge-

content is the highest. The results on two cells of the same thickness, with and without profiling of hydrogen dilution during growth, are shown in Table I. The cells were deposited on ss substrates with silver/zinc oxide back reflector. Measurements were made under global AM1.5 illumination with a $\lambda > 610$ nm cut-on filter to more appropriately evaluate the a-SiGe alloy solar cells. It is clearly seen that hydrogen dilution profiling improves the fill factor of the cell, indicating a better transport property of the minority carriers.

It is also interesting to point out that profiling of hydrogen dilution improves the quality of both a-Si and a-SiGe alloy solar cells, but the profiling directions are different. For a-Si alloy cells, since there is a tendency toward transition to microcrystallinity with increasing thickness, the dilution has to be reduced as the film thickness increases. For the a-SiGe alloy with the graded bandgap structure, on the other hand, since the Ge-concentration increases as a function of thickness, the hydrogen dilution has to increase as the thickness increases.

3. Conclusion

We have used the measurement of V_{oc} as a tool to obtain the amorphous-to-microcrystalline transition in a-Si and a-SiGe alloy solar cells. For a given thickness, the critical amount of hydrogen dilution at the threshold is found to increase as the Ge-concentration increases. This has helped us in designing high efficiency graded bandgap a-SiGe alloy solar cells in which hydrogen dilution increases with increasing Ge-content during the growth of the intrinsic layer.

4. Acknowledgement

REFERENCES

[1] J. Yang, A. Banerjee, and S. Guha. "Triple-junction amorphous silicon alloy solar cell with 14.6% initial and 13.0% stable conversion efficiencies," Appl. Phys. Lett. **70**, 2975 (1997).

[2] D.V. Tsu, B.S. Chao, S.R. Ovshinsky, S. Guha, and J. Yang. "Effect of hydrogen dilution on the structure of amorphous silicon alloys," Appl. Phys. Lett. **71**, 1317 (1997).

[3] J. Koh, Y. Lee, H. Fujiwara, C.R. Wronski, and R.W. Collins. "Optimization of hydrogenated amorphous silicon *p-i-n* solar cells with two-step *i* layers guided by real-time spectroscopic ellipsometry," Appl. Phys. Lett. **73**, 1526 (1998).

[4] S. Guha, J. Yang, D.L. Williamson, Y. Lubianiker, J.D. Cohen, and A.H. Mahan. "Structural, defect, and device behavior of hydrogenated amorphous Si near and above the onset of microcrystallinity," Appl. Phys. Lett. **74**, 1860 (1999).

[5] A. Matsuda. "Control of plasma and surface conditions for low defect density a-Si:H at high growth rates," *Conf. Record 25th IEEE Photovoltaics Specialists Conference* (IEEE, New York, 1996), p. 1029.

[6] S. Guha, J. Yang, A. Pawlikiewicz, T. Glatfelter, R. Ross, and S.R. Ovshinsky. "Band-gap profiling for improving the efficiency of amorphous silicon alloy solar cells," Appl. Phys. Lett. **54**, 2330 (1989).

TABLE I. J-V characteristics for $\lambda > 610$ nm of graded bandgap a-SiGe alloy solar cells with and without hydrogen profiling.

Hydrogen Profiling	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	P_{max} (mW/cm^2)
Yes	9.25	4.64	0.782	0.642
No	9.35	4.46	0.785	0.608